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Abstract

The NASA Glenn Research Center (GRC) is conducting in-house research on rare-earth permanent magnets and linear alternators to assist in developing free-piston Stirling convertors for radioisotope space power systems and for developing advanced linear alternator technology. This research continues at GRC, but, with the exception of Advanced Stirling Radioisotope Generator references, the work presented in this paper was conducted in 2005. A special arc-magnet characterization fixture was designed and built to measure the *M-H* characteristics of the magnets used in Technology Demonstration Convertors developed under the 110-W Stirling Radioisotope Generator (SRG110) project. This fixture was used to measure these characteristics of the arc magnets and to predict alternator demagnetization temperatures in the SRG110 application. Demagnetization tests using the TDC alternator on the Alternator Test Rig were conducted for two different magnet grades: Sumitomo Neomax 44AH and 42AH. The purpose of these tests was to determine the demagnetization temperatures of the magnets for the alternator under nominal loads. Measurements made during the tests included the linear alternator terminal voltage, current, average power, magnet temperatures, and stator temperatures. The results of these tests were found to be in good agreement with predictions. Alternator demagnetization temperatures in the Advanced Stirling Convertor (ASC—developed under the Advanced Stirling Radioisotope Generator project) were predicted as well because the prediction method had been validated through the SRG110 alternator tests. These predictions led to a specification for maximum temperatures of the ASC pressure vessel.

Introduction

As part of the NASA radioisotope power system development, the NASA Glenn Research Center (GRC) is conducting an in-house technology project that previously supported the Department of Energy (DOE), Lockheed-Martin (LM), and the Infinia Corporation by developing a high-efficiency 110-W Stirling Radioisotope Generator (SRG110) for possible use on future NASA space science missions (Refs. 1 to 3). The SRG110 development has been stopped, and recent program changes have been made to increase the specific power of the generator. This effort is supporting DOE, LM, and Sunpower Inc. in the development of the Advanced Stirling Radioisotope Generator (ASRG). As a part of this in-house

[1] Gene E. Schwarze, retired.

effort, GRC is conducting research on permanent magnets and linear alternators to assist in developing the Stirling power convertor for space qualification and mission implementation. The in-house effort includes both analytical (finite-element modeling) and experimental research on magnets and linear alternators (LAs). The majority of the work in this paper was conducted for the SRG110 project in 2005. In 2000, GRC developed a three-dimensional magnetostatic Maxwell model of the Technology Demonstration Convertor (TDC) linear alternator (LA used in SRG110) (Refs. 4 and 5). The model was used to predict the temperature that would cause demagnetization of the initially selected NdFeB magnets (Ugimag 40HC2) used in the alternator. The prediction for these magnets was later verified through a linear alternator demagnetization test conducted by Infinia.

GRC identified several other grades of neodymium-iron-boron (NdFeB) magnets as potential replacement candidates that could offer improvements in temperature margin based on the *M-H* characteristics provided by the vendor. All of the identified magnet grades offered superior intrinsic coercivity (resistance to demagnetization) in comparison with the TDC LA baseline magnets without sacrificing magnet remanence. The magnetostatic model of the TDC LA was used to predict the demagnetization temperatures for each of these grades in the TDC application. The predictions assumed nominal magnetic properties for each magnet grade.

Of the four new magnet grades identified by GRC, LM selected the two magnet grades (Sumitomo Neomax 44AH and 42AH) with the highest remanence for further consideration. LM asked GRC to perform demagnetization tests on these two magnet grades in the TDC application to confirm the predictions.

In 2004, an arc-magnet characterization paddle was fabricated to measure the intrinsic induction (intrinsic induction versus magnetizing force, *M-H*) curves of the TDC LA magnets (Ref. 6). Initially, only the magnetizing force *H* measurements seemed reasonable. The *B* measurements were well below expectations because of leakage flux at the curved ends of the magnets. In 2005, special electromagnet pole extensions were designed and fabricated to improve the accuracy of the *M-H* measurements by reducing the leakage flux at the curved ends of the magnets. The *M-H* curves measured using the arc-magnet characterization paddle and pole extensions are now shaped more like those of the cube magnets.

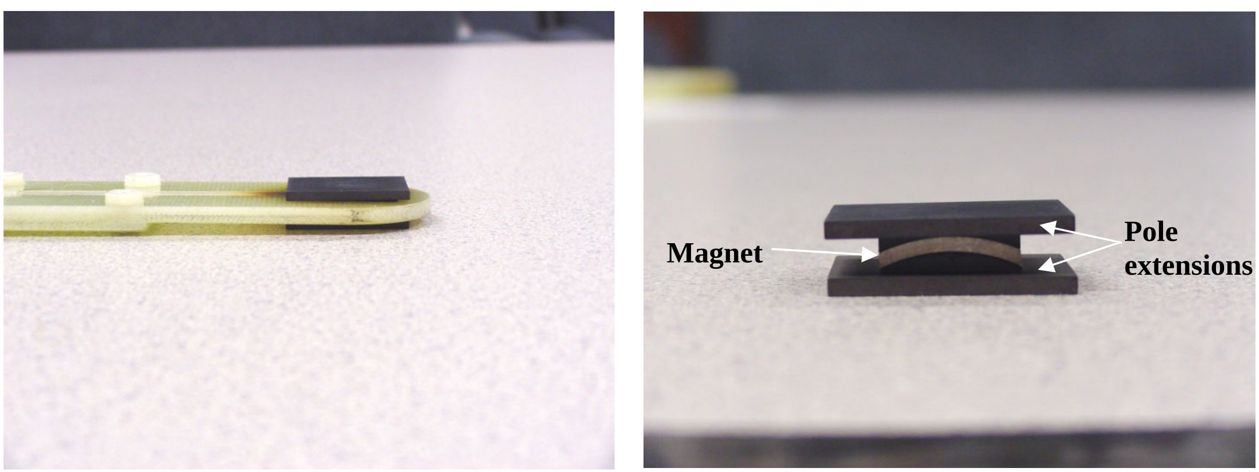
Nomenclature

ASRG	Advanced Stirling Radioisotope Generator
ATR	Alternator Test Rig
B_r	remanence (T)
BOM	beginning of mission
DOE	Department of Energy
GRC	Glenn Research Center
H	magnetizing force (kOe)
H_c	coercivity (kOe)
H_{ci}	intrinsic coercivity (kOe)
H_k	knee location (as defined in this report) on magnetization curve (kOe)
LA	linear alternator
LCR	Induction, Capacitance, Resistance
LM	Lockheed-Martin
M	magnetization (T)
NdFeB	neodymium-iron-boron
NIST	National Institute of Standards and Technology
RMS	Root Mean Square
RTV	room temperature vulcanized silicone rubber
SRG110	Stirling Radioisotope Generator, 110 We
TDC	Technology Demonstration Convertor

Arc-Magnet Characterization

The magnetic properties of the arc magnets were measured both before and after the demagnetization tests. The procedure used to measure the *M-H* characteristics of the arc magnets is basically the same as that discussed by Niedra (Ref. 7) for cube magnets. The only difference is in the characterization paddle used to make the measurements. An arc-magnet characterization paddle designed specifically for the TDC LA magnets was used to measure the *M-H* curve for all arc-shaped magnets at room temperature (23 °C). The arc-magnet characterization paddle, along with the electromagnet pole extensions and the arc-magnet nickel standard sandwiched in between, is shown in Figure 1. The pole extensions shown in Figure 1(b) were designed by Niedra and Geng in collaboration with Dr. Reinhold Strnat of KJS Associates, Inc., of Indianapolis, Indiana. These extensions are used to control the demagnetization field applied to the arc magnet. The flat, square-shaped surfaces of the pole extensions fit snugly between the flat and parallel pole extensions of a 10-in., variable-gap electromagnet. The electromagnet pole extensions are a spatially fixed part of a temperature control fixture. The electromagnet is used to apply an external demagnetizing field to the magnet. The arc-magnet characterization paddle is fitted with built-in magnetization and field-strength-sensing coils that are used to measure the *M-H* characteristics of the arc-shaped magnets. The arc-magnet nickel standard is used as the calibration reference, and its material is traceable to the National Institute of Standards and Technology (NIST) through KJS.

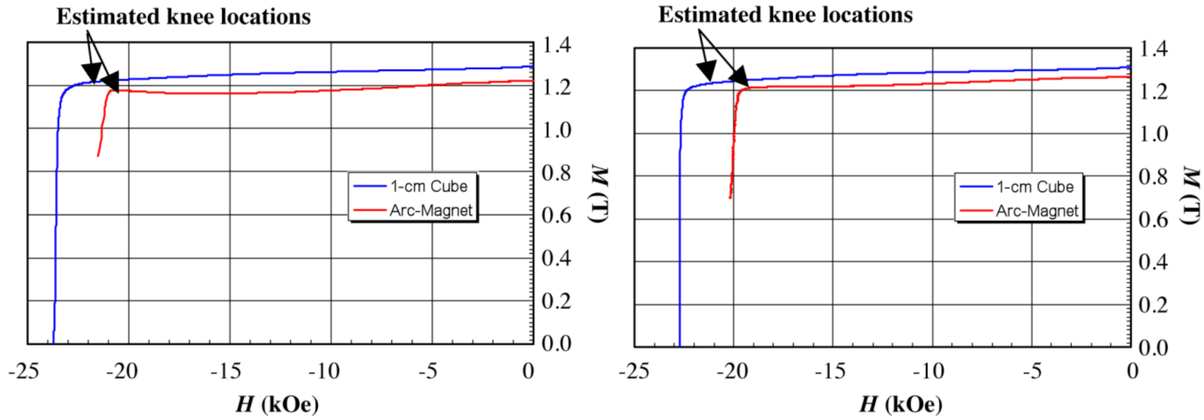
For the 42AH magnets, the measurements indicated a range of intrinsic coercivity H_{ci} between 22.8 and 24.3 kOe (vendor minimum H_{ci} for cube-shaped magnets = 24 kOe at 20 °C) and a range of remanence B_r between 1.22 and 1.24 T (vendor minimum B_r for cube-shaped magnets = 1.28 T at 20 °C) for the eight arc-shaped alternator magnets. For the 44AH magnets, the measurements indicated a range of H_{ci} between 20.5 and 21.3 kOe (vendor minimum H_{ci} for cube-shaped magnets = 21 kOe at 20 °C) and a range of B_r between 1.25 and 1.27 T (vendor minimum B_r for cube-shaped magnets = 1.30 T at 20 °C) for the eight arc-shaped alternator magnets. Both the H_{ci} and B_r measurements for the arc-shaped magnets were slightly below the vendor minimum values for cube-shaped magnets. It should be noted that although the arc-shaped magnet measurements were repeatable, the accuracy of the measurements is unknown at this time. The difference between the arc- and cube-shaped magnet measurements could be due to geometry or the effect of the machining process, but it also may be due to differences in the measurement techniques.



(a) Arc-magnet characterization paddle

(b) Pole extensions with nickel arc-magnet standard

Figure 1.—Arc-magnet characterization paddle, pole extensions, and nickel arc-magnet standard.



(a) *M-H* Curves for 42AH Magnets

(b) *M-H* Curves for 44AH Magnets

Figure 2.—Cube-shaped magnet characterization data compared with Arc-magnet characterization data at 23 °C.

Figure 2 shows a comparison between the *M-H* curves measured for cube-shaped magnet samples and for arc-shaped magnet samples. These plots show that the knee location of the 42AH arc-shaped magnet *M-H* curve is about 1 kOe less than that of a cube-shaped magnet sample, whereas the knee location of the 44AH arc-shaped magnet *M-H* curve is about 2 kOe less than that of a cube-shaped magnet. The points of onset of rapid demagnetization, or knee locations (H_k), as referred to in this report, were determined by visual inspection of the *M-H* curves. Recalculating the predicted demagnetization temperature based on the *M-H* curve for the magnet with the least demagnetization resistance (i.e., lowest absolute H_k) of the 42AH arc-shaped magnets resulted in a new prediction of 132 °C, whereas the initial prediction was 136 °C. The same procedure applied to the 44AH arc-shaped magnets resulted in a new prediction of 117 °C, whereas the previous prediction was 122 °C. The methodology for predicting the onset of demagnetization temperatures is described in Appendix A.

Demagnetization Test

Apparatus and Procedure

The GRC alternator test rig (ATR) was used to drive the test alternator for this test. The ATR features a Sunpower linear motor (DTR0101) as the drive motor. The DTR0101 is a variable-stroke and variable-frequency linear motor that can be used to drive linear alternators at mover amplitudes up to 6.5 mm and frequencies up to 120 Hz. The DTR0101 can deliver a nominal output of 150 W at 60 Hz and a stroke of 13 mm. It is powered using a Chroma model 6404 programmable alternating-current (AC) source. A Sorensen model DCR80–6B direct-current (DC) power supply is used to provide power to an electric resistance heater blanket that is wrapped around the test alternator to control temperature. The heater blanket is wired to minimize the magnetic field that it generates. The DTR0101, power supplies, data acquisition system, and all support equipment are collectively referred to as the ATR, which is shown in Figure 3.

A high-temperature red room temperature vulcanized (RTV) silicone rubber was used to secure the arc magnets to the stator laminations. A bead of RTV was placed along the straight edges of each magnet. This method of securing the magnets allowed for easy removal after the test had been completed so that a posttest magnet characterization could be performed.

Type T thermocouples were used to measure the temperatures of the magnets. Type T thermocouples were selected for this test since both conductors (copper and constantan) are nonmagnetic. One thermocouple was epoxied to each of the eight magnets. Thermocouples were also placed with Kapton tape on the outside cylindrical surface of the stator laminations adjacent to each of the four pole/coils.

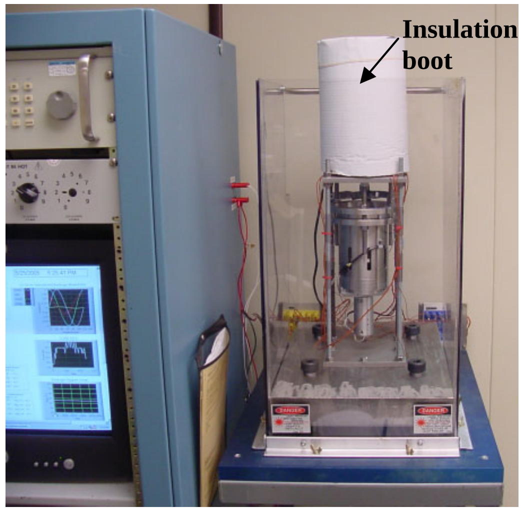


Figure 3.—TDC 55-We linear alternator covered with insulation boot and mounted on ATR.

A set of baseline operating conditions was selected for the demagnetization tests. The baseline mover amplitude was 6.1±0.05 mm and the baseline magnet temperature was 80±0.5 °C. The alternator was maintained at the design frequency of 82 Hz. The inductance of the test alternator was measured with an HP 4284A Precision Induction–Capacitance-Resistance (LCR) meter to determine the tuning capacitance required to achieve full alternator power output. The tuning capacitor was wired in series with a resistive load such that the inductive reactance canceled the capacitive reactance. The load resistance was adjusted until the output power of the alternator was approximately 68.8 W (SRG beginning of mission (BOM) predicted power is about 68.6 W), while maintaining the baseline mover amplitude and magnet temperature. The load resistance needed to achieve this alternator output power was 75.3 Ω, and the resultant current was 0.97 A, root mean square (A_{RMS}). The load resistance and tuning capacitance were held constant throughout the demagnetization test.

The alternator magnets were heated using a 360-W fiberglass-reinforced silicone-rubber heat blanket wrapped around the alternator stator and end rings as shown in Figure 4. Heat was conducted from the blanket, through the stator, and to the magnets. The magnet temperatures were raised gradually (at a rate of about 2 °C/min) to prevent localized hot spots at the magnet/stator interface. An insulation boot was placed over the alternator while the magnets were heated as shown in Figure 3.

For cooling the magnets to the baseline temperature of 80 °C, the insulation boot was slid up about 1.5 in. to expose the ATR/LA interface ring as shown in Figure 5. A muffin fan positioned near this interface ring was then used to convectively cool the interface ring, which helped to conduct heat away from the magnets. The magnets could be cooled in this manner at a rate of about 2 °C/min.

The highest magnet temperature of the eight magnets was initially increased in increments of 5 °C. When the magnet temperature reached within 10 °C of the predicted demagnetization temperature, the increment was reduced to 2 °C. Data were recorded after each incremental increase in temperature before the magnets were returned to baseline operating conditions. Then the data were recorded again. The maximum magnet temperatures reached during this test were 151 °C for the 42AH magnets and 134 °C for the 44AH magnets.

Complete demagnetization of the alternator magnets was purposely avoided to reduce the chance of magnet separation from the stator laminations. The magnetic forces of the magnets along with beads of RTV were relied on to keep the magnets fixed to the stator poles. Complete demagnetization would have placed the entire burden of holding the magnets onto the RTV.

The AC-source RMS voltage and current as well as the linear alternator terminal RMS voltage and current, average power, eight magnet temperatures, and four stator temperatures were recorded at each test operating point.

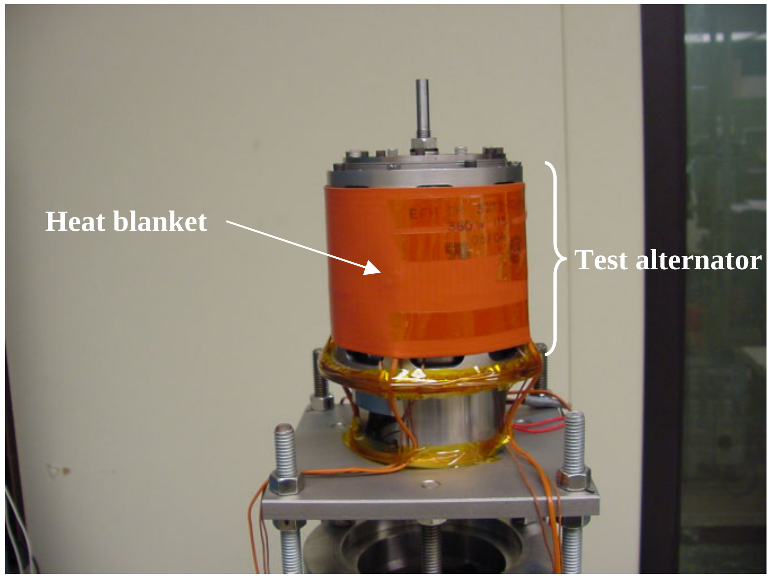


Figure 4.—A 55-We linear alternator mounted on ATR with 360-W thermal blanket wrapped around stator and end rings.

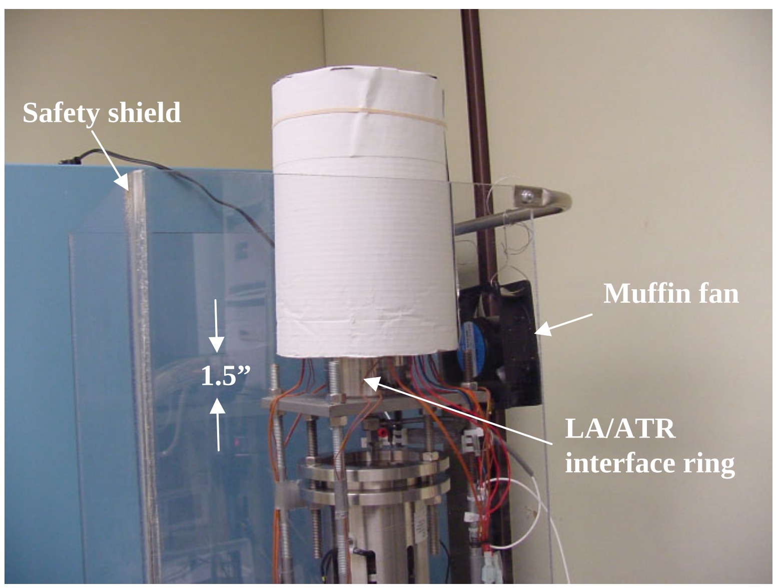


Figure 5.—Insulation boot position when cooling magnets.

Demagnetization Test Results

In Figure 6 the alternator terminal voltage measured at the baseline alternator operating conditions (frequency = 82 Hz, mover amplitude = 6.1 mm, and magnet temperature = 80 °C) is plotted as a function of the maximum magnet temperature reached before the magnets were returned to baseline temperature. These plots indicate that the onset of magnet demagnetization occurred between 131 and 135 °C for the 42AH magnets and between 116 and 120 °C for the 44AH magnets. These results agree well with the GRC prediction of 132 and 117 °C for magnet grades 42AH and 44AH, respectively.

It should be noted that Figure 6 indicates the degradation of magnet B_r as a function of magnet temperature. It does not give any indication of degradation regarding H_{ci}. Tables I and II list the magnetic properties of the arc-shaped magnets measured at room temperature (2 °C) both before and after the LA demagnetization test. The information shown in the tables includes the pretest and posttest magnet B_r, H_k,

and H_{ci}. For the pretest data, the arc magnets were fully charged, characterized, and recharged prior to insertion into the alternator. For the posttest data, the magnets were removed from the alternator, characterized, and recharged in preparation for reuse. Comparing the pretest and posttest measurements, Table I shows that the average 42AH magnet B_r dropped by 1.7 percent, whereas H_k dropped by 0.7 percent during this test, and Table II shows that the average 44AH magnet B_r dropped by 2.1 percent, whereas H_k dropped by 1.7 percent.

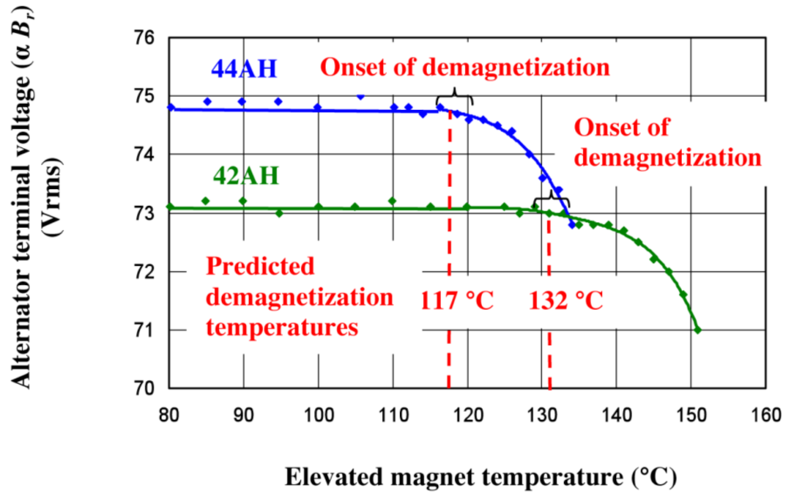


Figure 6.—Alternator terminal voltage at baseline conditions (80 °C) following operation at elevated temperatures.

TABLE I.—42AH ARC-MAGNET CHARACTERIZATION DATA AT 23 °C

Magnet identification	Pretest			Posttest			Percent change		
	B_r (T)	H_k (kOe)	H_{ci} (kOe)	B_r (T)	H_k (kOe)	H_{ci} (kOe)	B_r	H_k	H_{ci}
42AH–1	1.24	–21.0	–23.1	1.20	–20.7	–22.7	–3.2	–1.4	–1.7
42AH–2	1.24	–20.8	–23.4	1.22	–20.6	–23.0	–1.6	–1.0	–1.7
42AH–3	1.23	–20.9	–24.1	1.22	–20.7	–24.0	–0.8	–1.0	–1.7
42AH–4	1.23	–20.6	–23.0	1.20	–20.6	–22.7	–2.4	0.0	–1.3
42AH–5	1.23	–21.1	–24.3	1.22	–21.1	–22.9	–0.8	0.0	–5.8
42AH–6	1.23	–20.6	–23.5	1.22	–20.6	–22.4	–0.8	0.0	–4.7
42AH–7	1.23	–20.6	–23.6	1.21	–20.4	–23.1	–1.6	–1.0	–2.1
42AH–8	1.22	–20.6	–22.8	1.19	–20.3	–22.6	–2.5	–1.5	–0.9

TABLE II.—44AH ARC-MAGNET CHARACTERIZATION DATA AT 23 °C

Magnet identification	Pretest			Posttest			Percent change		
	B_r (T)	H_k (kOe)	H_{ci} (kOe)	B_r (T)	H_k (kOe)	H_{ci} (kOe)	B_r	H_k	H_{ci}
44AH–1	1.25	–19.7	–21.0	1.24	–19.4	–20.7	–0.8	–1.5	–1.4
44AH–2	1.27	–19.5	–20.8	1.24	–19.1	–20.4	–2.4	–2.1	–1.9
44AH–3	1.27	–19.2	–20.5	1.22	–18.9	–20.2	–3.9	–1.6	–1.5
44AH–4	1.26	–19.6	–20.9	1.24	–18.9	–20.2	–1.6	–3.6	–3.3
44AH–5	1.25	–19.8	–21.1	1.24	–19.4	–20.7	–0.8	–2.0	–1.9
44AH–6	1.25	–19.9	–21.3	1.22	–19.3	–20.6	–2.4	–3.0	–3.3
44AH–7	1.26	–19.5	–20.8	1.24	–19.5	–20.8	–1.6	0.0	0.0
44AH–8	1.27	–19.2	–20.5	1.23	–19.2	–20.5	–3.1	0.0	0.0

Advanced Stirling Radioisotope Generator Discussion

The method for predicting demagnetization temperatures in an alternator was applied to the ASC as part of the ASRG project. A three-dimensional magnetostatic Maxwell model was created of the ASC alternator (used in the ASRG) to predict the temperature that would cause the LA magnets to demagnetize. The *M-H* characteristics for the ASC LA magnets also were measured at GRC and compared with vendor data to verify that appropriate values were being used in the model. This predicted value for demagnetization contributed to determining a specification for the ASC pressure vessel maximum temperature (the ASC LA is housed in the ASC pressure vessel). The final specification was determined to be 115 °C for the maximum ASC pressure vessel temperature (Ref. 8), which included some margin.

Conclusions

The magnetic properties of the arc magnets used in this test were all slightly below the vendor minimum specifications for cubes. The predicted demagnetization temperature based on the arc-magnet *M-H* curve was 132 °C for 42AH magnets and 117 °C for 44AH magnets. In general, the predicted demagnetization temperatures were in good agreement with the test data. The demagnetization temperature of the Technology Demonstration Convertor (TDC) linear alternator can be accurately predicted provided that the magnetic properties of the actual alternator magnets are known. The shape of a magnet may affect its magnetic properties. Vendor data are typically given for cube-shaped magnets. However, variation of intrinsic properties with magnet shape can be expected.

This method for predicting alternator demagnetization temperatures was validated using the TDC alternator tests on the Alternator Test Rig. The same method was then used to predict alternator demagnetization temperatures for the Advanced Stirling Radioisotope Generator (ASRG). This prediction was part of the method for determining the specification for the ASRG maximum convertor pressure vessel temperature.

Appendix A—Methodology Used to Predict Demagnetization Temperatures

A three-dimensional magnetostatic model of the TDC linear alternator was used to calculate the peak magnetic field strength at various temperatures for the arc magnets with the assumption of first 42AH magnets, then 44AH magnets, for the mover amplitude (6.1 mm) and alternator current (0.97 A_{RMS}) as selected for the demagnetization tests. Demagnetization fields were calculated as documented by Geng (Ref. 5). Figure 7 shows the results of these predictions plotted along with curves that represent the estimated knees of the 42AH and 44AH arc-magnet intrinsic induction curves. The intersection of the lines represents the predicted demagnetization temperature for the two magnet grades. The predicted demagnetization temperature for the TDC linear alternator equipped with 42AH magnets and with the assumption of normal loads (no current spikes) was approximately 132 °C, whereas the predicted demagnetization temperature for the 44AH magnets was approximately 117 °C.

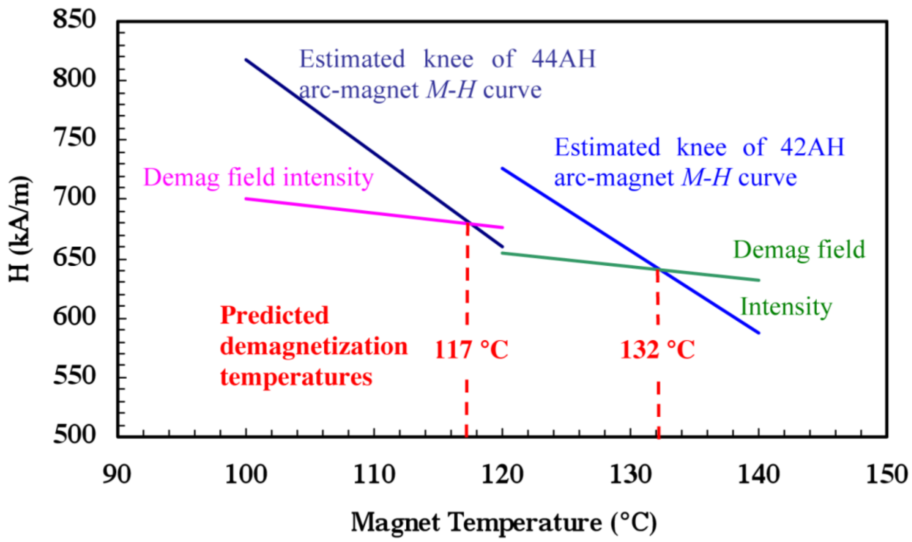


Figure 7.—Sensitivity of resistance to demagnetization and maximum localized demagnetization field intensity.

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14. ABSTRACT
The NASA Glenn Research Center (GRC) is conducting in-house research on rare-earth permanent magnets and linear alternators to assist in developing free-piston Stirling convertors for radioisotope space power systems and for developing advanced linear alternator technology. This research continues at GRC, but, with the exception of Advanced Stirling Radioisotope Generator references, the work presented in this paper was conducted in 2005. A special arc-magnet characterization fixture was designed and built to measure the M-H characteristics of the magnets used in Technology Demonstration Convertors developed under the 110-W Stirling Radioisotope Generator (SRG110) project. This fixture was used to measure these characteristics of the arc magnets and to predict alternator demagnetization temperatures in the SRG110 application. Demagnetization tests using the TDC alternator on the Alternator Test Rig were conducted for two different magnet grades: Sumitomo Neomax 44AH and 42AH. The purpose of these tests was to determine the demagnetization temperatures of the magnets for the alternator under nominal loads. Measurements made during the tests included the linear alternator terminal voltage, current, average power, magnet temperatures, and stator temperatures. The results of these tests were found to be in good agreement with predictions. Alternator demagnetization temperatures in the Advanced Stirling Convertor (ASC-developed under the Advanced Stirling Radioisotope Generator project) were predicted as well because the prediction method had been validated through the SRG110 alternator tests. These predictions led to a specification for maximum temperatures of the ASC pressure vessel.

15. SUBJECT TERMS
Stirling engines; Stirling cycle; Linear alternators; Permanent magnets

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